

SPECTROSCOPIC INVESTIGATION OF ELECTRIC FIELD  
FLUCTUATIONS IN A STEADY PLASMA

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## SPECTROSCOPIC INVESTIGATION OF ELECTRIC FIELD

### FLUCTUATIONS IN A STEADY PLASMA

Our primary goal was to see whether in a steady plasma, electric fluctuations caused by plasma oscillations were observable.

To answer this question we looked for plasma satellites induced by electric field fluctuations in a helium plasma created by an electron beam. This method proposed by Baranger and Mozer<sup>1</sup> predicts the satellite lines disposed symmetrically in pairs about a forbidden atomic line and separated from it by the frequency of the electric field oscillations. Such plasma satellites were observed by Kunze and Griem<sup>2</sup>, Kunze et al<sup>3</sup> in a theta pinch and by Cooper and Ringler<sup>4</sup> in a steady-state discharge to which they applied externally a microwave field.

## II

## EXPERIMENTAL CONDITIONS

### 1. Electron Gun

The constructed electron gun uses a tungsten cathode impregnated with barium oxide. The beam current density obtainable from this cathode is  $40 - 50 \text{ A/cm}^2$  for microsecond pulses,<sup>5,6</sup> but we have used them in a D. C. mode. Figures 1 and 2 show the experimental setup. The filament of the cathode is heated with an alternating current through a filament transformer insulated for 2500 V. The negative high potential is applied to the cathode, whereas the anode and the diaphragms are grounded. The electrons are accelerated in the electric field between cathode and anode and have a constant speed after the anode. In order to obtain a homogeneous electric field, the cathode is surrounded by a plate parallel to the anode, and a tungsten grid is put across the hole of the anode.

The emission capability of the cathode depends on its temperature. Table 1 shows some heating conditions. The temperature is measured at the rear of the cathode because we cannot see its front.

The electron beam emitted from the cathode (10 mm diameter) is a little divergent (a few degrees), so the diameter of the diaphragms have to be the largest possible. We choose 16 mm for the anode and the first diaphragm (2 and 5 on Fig. 2), and 7 mm for the diaphragm at the entrance of the observation cell (7 on Fig. 2). On the other hand, the distance between anode and cathode which seems to give the best beam is of the order of 4 mm. Table 2 gives some electron currents obtained with these conditions. We see from this table that most of the electron beam goes to the anode and to the diaphragms, and in order to increase the beam in the cell we applied a longitudinal magnetic field created with two coils.

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Table 1. Heating Conditions of the Cathode; Pressure  $10^{-5}$  Torr

V Volts	A. C. I A	T(°C)
2.2	3.4	
3.0	3.9	
3.7	4.3	
4.5	4.75	
5.2	5.15	
6.0	5.6	
6.7	5.9	$1150 \pm 50$
7.5	6.5	$1275 \pm 50$

Table 2

Power supply		Anode Current	Current at Collector
H. V.			
V Volts	I mA	I mA	I mA
100	10	7	0.003
200	20	18	0.16
300	35	33	0.32
400	52	49	0.52
500	72	66	0.77
600	90	84	1.1
700	110	105	1.4
800	130	120	1.9
900	150	135	2.6
1000	155	140	2.8

The following table gives the variations of the current with the magnetic field.

Table 3

Experimental Conditions: high voltage 1000 v  
first coil 100 turns  
second coil 80 turns

Coil Current	H. V. Current	Anode Current	Current at Collector
I(A)	I(mA)	I(mA)	I(mA)
0	150	135	2.5
5	-	-	-
10	-	-	2.7
15	-	-	3.1
20	-	-	3.7
25	-	-	4.3
30	-	-	5.5
35	-	-	7
40	-	130	10
45	-	125	22
50	-	100	44

The results show that the increasing magnetic field gives a higher final current, while the current on the anode and on the diaphragms is decreasing.

The power supply used for the coils, gives 50 A at 20 V. In a second setup we constructed bigger coils in order to increase the magnetic field. A typical final current obtained with two coils of 170 turns each was then 80 mA. The first coil must be close to the last diaphragm.

## 2. Magnetic Coils

They were built with 3.5 mm-diameter copper wire; each coil has 170 turns, they are 8 cm long, the inside diameter is 12 cm and the outside diameter is 18 cm. A rough value of the magnetic field at the observation point which is about 2 cm far away from the end of each coil, is:

$$B[\text{Wb/m}^2] = 1.3 \times 10^{-5} \times I(\text{A})$$

### 3. Comment

When we fill gas into the cell, the pressure in the electron gun increases and the cathode is cooled by the gas; in order to obtain the same electron beam as at the pressure of  $10^{-5}$  Torr, we have to increase the power dissipated in the filament in order to increase the cathode temperature. However, we cannot increase this power arbitrarily since this would damage the cathode. Consequently, when the pressure increases in the cell, the electron current decreases.

#### 4. Spectroscopic Apparatus

The spectral range  $3000 \text{ \AA} - 5000 \text{ \AA}$  has been investigated with a Jarrel-Ash 0.5 m Ebert spectrometer with an EMI photomultiplier. The grating, blazed for  $5000 \text{ \AA}$ , has 1180 lines/mm. The photomultiplier current is amplified and displayed on a strip-chart recorder. A typical scan is shown on Fig. 3. The scanning speed is  $2 \text{ \AA/mm}$ . In the second order with  $25 \mu$  slits, the half-width of the He I  $4471.479 \text{ \AA} 2p^3P_{2,1} - 4d^3D_{3,2}$  line is  $\Delta\lambda = 0.15 \text{ \AA}$ .

## RESULTS

1. Intensity of Various He I Lines

The intensities given in an arbitrary scale, are not corrected for the sensitivity of the monochromator and photomultiplier.

## Experimental Conditions:

Monochromator: first order, 25  $\mu$  slits

grating 1180  $\text{\AA}/\text{mm}$  blazed for 5000  $\text{\AA}$ ;

He:  $p \approx 5 \times 10^{-3}$  Torr

electron beam  $I \approx 30$  mA,  $V = 1000$  V with magnetic field  $B \approx 540$  Gauss;

observation between the two coils

$\lambda(\text{\AA})$	Transition	Intensity
3888.648	$2s \ ^3S_1 - 3p \ ^3P_{2,1}^0$	168
4387.929	$2p \ ^1P_1^0 - 5d \ ^1D_2$	20
4471.5	$2p \ ^3P^0 - 4d \ ^3D$	59
4713.3	$2p \ ^3P^0 - 4s \ ^3S_1$	8
4921.931	$2p \ ^1P_1^0 - 4d \ ^1D_2$	45
5015.678	$2s \ ^1S_0 - 3p \ ^1P_1^0$	155
5875.7	$2p \ ^3P^0 - 3d \ ^3D$	33

## 2. Electron Density Determination

A value of the Stark broadened electron density  $N_e$  can be obtained from the profile of spectral lines. We use the He I  $2p\ ^3P^0 - 9d\ ^3D$  transition at  $3587\ \text{\AA}$ . At our low densities the  $2p\ ^3P^0 - 4d\ ^3D$  transition at  $4471\ \text{\AA}$  is essentially not broadened, so its profile can be taken as the instrumental profile.

$\lambda(\text{\AA})$	Transition	half-width ( $\Delta\lambda_{1/2}$ ) ( $\text{\AA}$ )
4471.479	$2p\ ^3P_{2,1}^0 - 4d\ ^3D_{3,2}$	0.15
3587.270	$2p\ ^3P_{2,1}^0 - 9d\ ^3D$	0.22

We obtain thus a true half-width of the  $3587\ \text{\AA}$  line, of  $\Delta\lambda_{1/2} \approx 0.07\ \text{\AA}$ .

The relation  $\Delta\lambda_{1/2} = C(n^2) N_e^{2/3}$  gives the half-width; the value  $C$  for the 2 lines above depends mainly on the quantum number  $n$  of the upper level.

$N_e$  is the electron density. The variation of  $C$  with  $n$  can be determined from Gieske and Griem,<sup>7</sup> Fig. 5, and the density can be so estimated thus

to

$$N_e \approx 3 \times 10^{12} \text{ cm}^{-3}$$

### 3. Electron Temperature Measurements

The electron temperature in a plasma can be determined from the intensity ratio of suitably chosen spectral lines emitted by the same element.

#### A. Intensity ratio of the lines He II 4686 Å and He I 5875 Å as a function of temperature.

At high electron densities ( $N_e > 10^{18} \text{ cm}^{-3}$ ) the intensity ratio of the two lines can be derived from LTE populations of the upper levels. At low electron densities, the intensities of the lines and thus their ratio are determined by corona equilibrium relations. The intensity ratio has been calculated by Mewe<sup>8</sup> for electron temperatures between 2 and 11 eV for the entire density range  $10^{10} \leq N_e \leq 10^{19} \text{ cm}^{-3}$ .

Experimentally we find an intensity ratio of 0.1 without corrections for the sensitivity change of the monochromator-photomultiplier system. The intensity of the He II lines also changes very much with the experimental conditions (accelerating voltage, magnetic field). We obtain thus approximately

$$0.01 < \frac{I_{4686}}{I_{5876}} < 0.1$$

With this ratio and the determined approximate value of the electron density

$$N_e \sim 10^{12} \text{ cm}^{-3}$$

we can deduce the temperature from the calculation of Mewe:

$$\text{For } N_e = 1.28 \times 10^{10} \text{ cm}^{-3} \rightarrow 4.1 \text{ eV} < kT_e < 4.7 \text{ eV}$$

$$N_e = 1.28 \times 10^{14} \text{ cm}^{-3} \rightarrow 3.9 \text{ eV} < kT_e < 4.5 \text{ eV}$$

We can take

$$3.9 \text{ eV} < kT_e < 4.7 \text{ eV}$$

or

$$45 \times 10^3 \text{ }^\circ\text{K} < T_e < 54 \times 10^3 \text{ }^\circ\text{K}$$

This ratio has also been estimated by Griem<sup>9</sup> for  $kT_e$  in the range 3 - 7 eV and  $N_e < 10^{18} \text{ cm}^{-3}$ . The deduced temperature  $36 \times 10^3 \text{ }^\circ\text{K} < T_e < 42 \times 10^3 \text{ }^\circ\text{K}$  is not too different.

#### B. Helium singlet to triplet method.

This method suggested by Cunningham<sup>10</sup> uses ratios between the intensities of the lines  $\lambda 4713 \text{ \AA}$  ( $2^3\text{P} - 4^3\text{S}$ ) and  $\lambda 4921 \text{ \AA}$  ( $2^1\text{P} - 4^1\text{D}$ ). It is essentially applicable only at low electron densities. One serious limitation, however, is due to the fact that the cross sections for excitation to the upper levels are only poorly known. In addition, Drawin and Henning<sup>11</sup> have shown that the inclusion of collisions of the excited atoms with other plasma particles leads to intensity ratios which are much less temperature dependent than assumed originally by Cunningham. Their considerations show quite clearly, that this method is not suited for reliable temperature measurements. If we would take our observed ratio of 0.2, this would lead to a temperature of about  $10^6 \text{ }^\circ\text{K}$  after Cunningham, while this ratio should be nearly not possible at all after Ref. 11.

#### 4. He I Line Profiles

The line profiles of various He I lines show small bumps on each side of the center of the line. These bumps are on all lines and have been identified to be instrumental. Their intensities relative to the intensity of the line is of the order of  $10^{-4}$ . Possible plasma satellites are thus even weaker and we have an upper limit  $S_{\pm} < 10^{-4}$ . The intensity ratio of the satellites to the allowed line is given by Baranger and Mozer<sup>1</sup>.

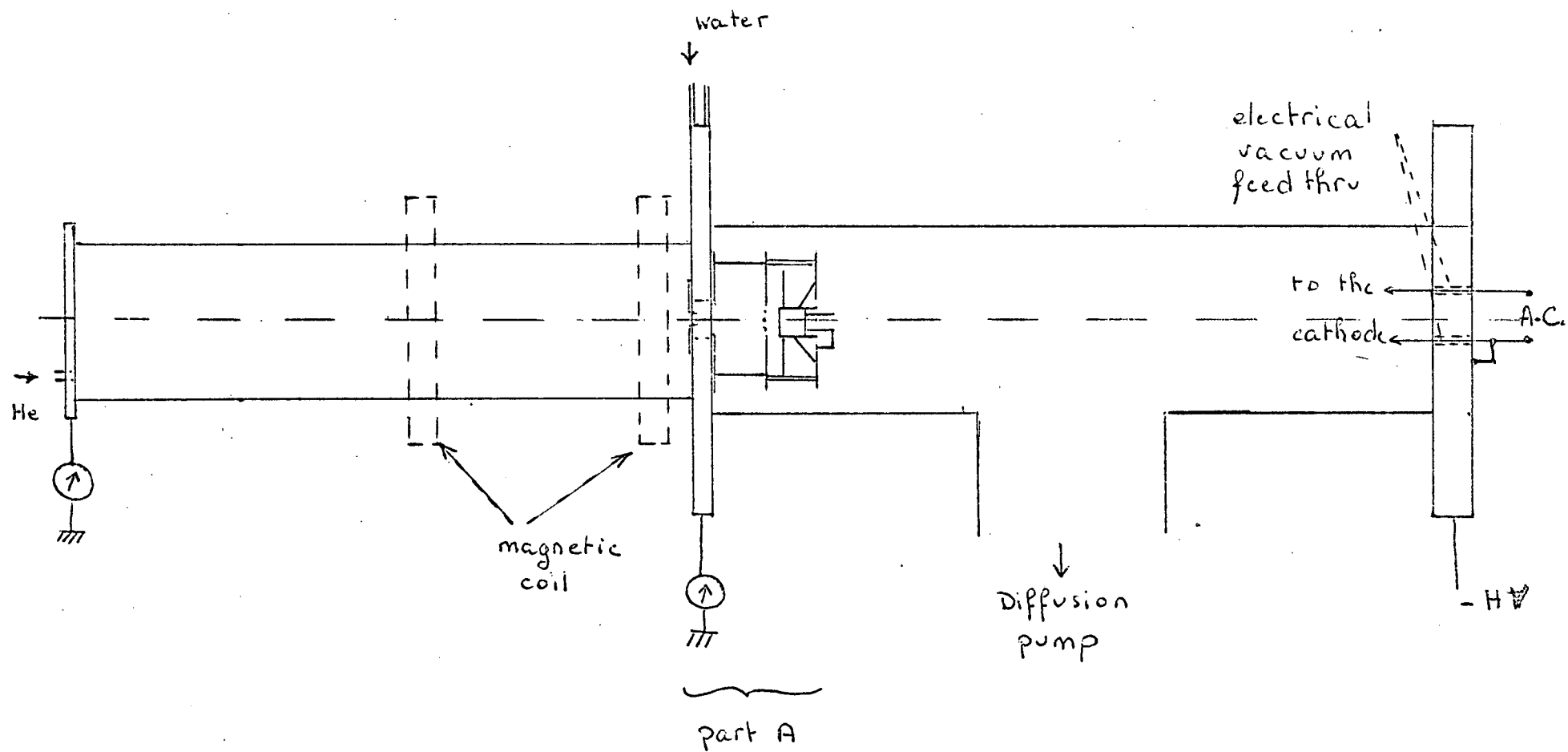
$$S_{\pm} = \hbar^2 \langle E_p^2 \rangle R_{\ell\ell} / 6m^2 e^2 (\Delta \pm \Omega)^2$$

At our densities  $\Omega$  is small compared to  $\Delta$ . We can obtain thus an upper limit for possible electric field fluctuations.

$$\sqrt{\langle E^2 \rangle} < 200 \frac{v}{m}$$

## References

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scale 1/3

figure 1 electron gun

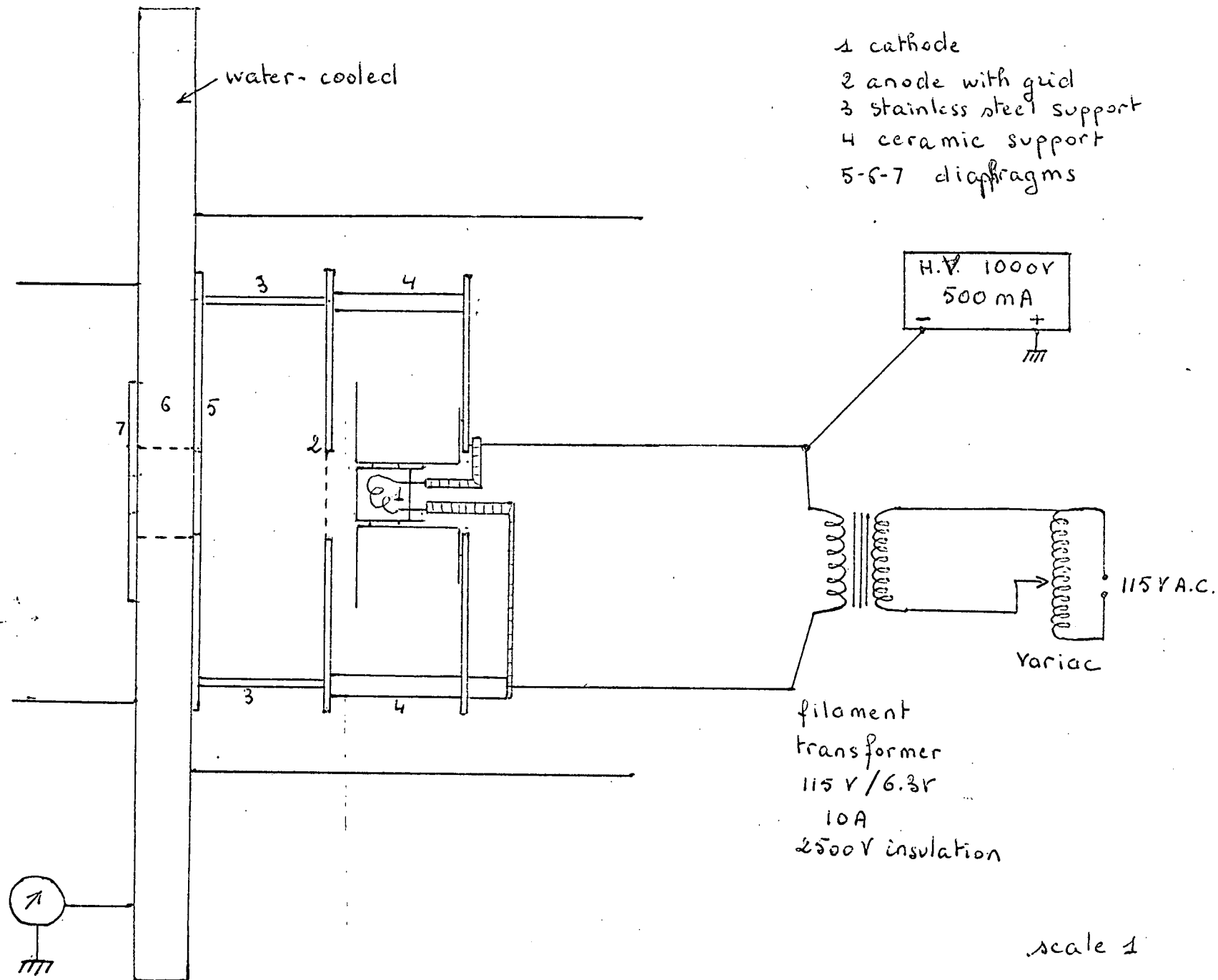


figure 2 part A . cathode - anode

He I 4471 Å  
 $2p^3P^o - 4d^3D$

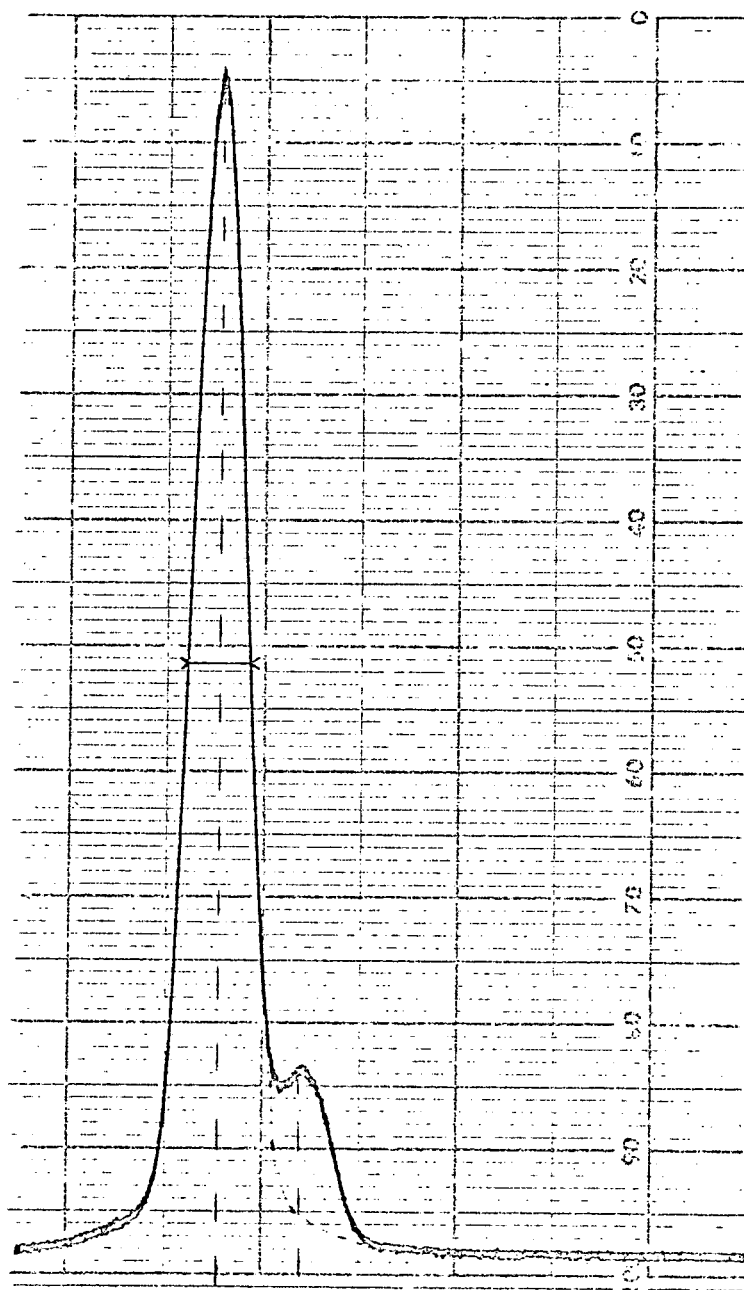


Figure 3

$2p^3P^o_{2,1} - 4d^3D_{3,2}$   
 4471.479  
 4471.682  
 $2p^3P^o_{2,1} - 4d^3D_1$

Jarrel-Ash 0.5m  
 slits 25μ, second order  
 electron-beam 30mA  
 He pressure  $5 \times 10^{-3}$  Torr

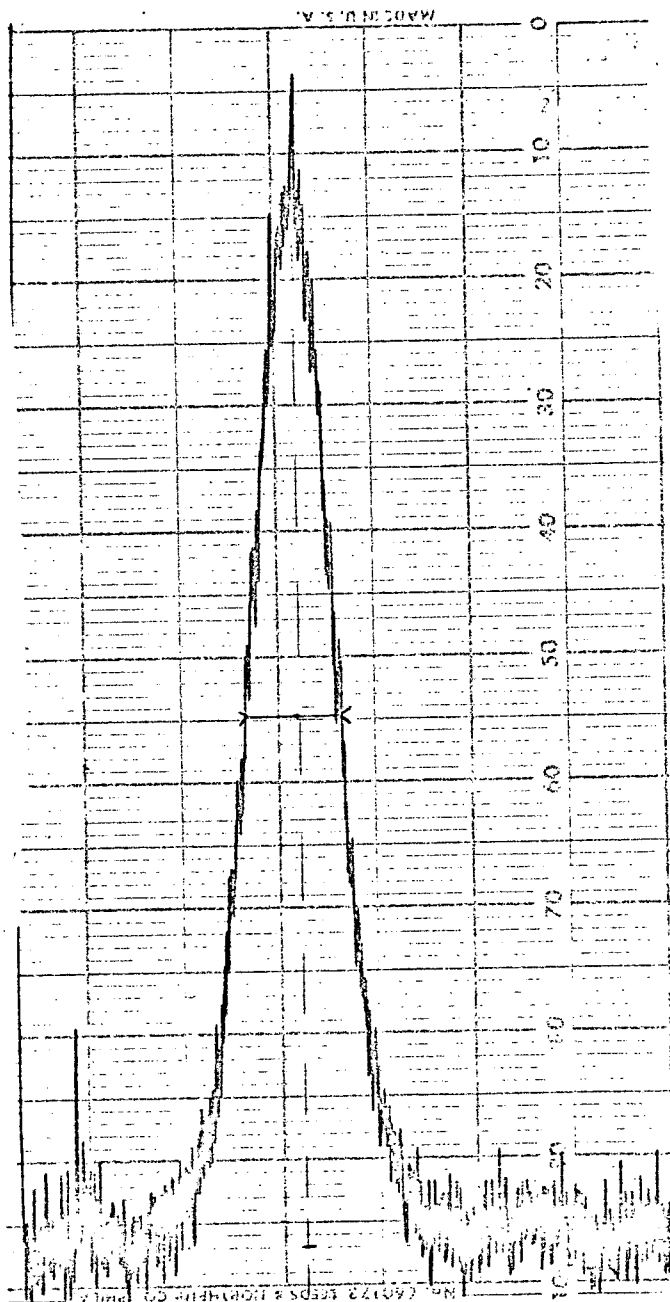
$\text{He I } 3587 \text{ \AA}$ 
 $2p^3P^o - 9d^3D$ 

 $2p^3P^o_2 - 9d^3D$   
 3587.270

Figure 4

Jarrel-Ash 0.5m  
 slits 85μ, second order  
 electron beam 30 mA  
 He pressure  $5 \times 10^{-3}$  Torr

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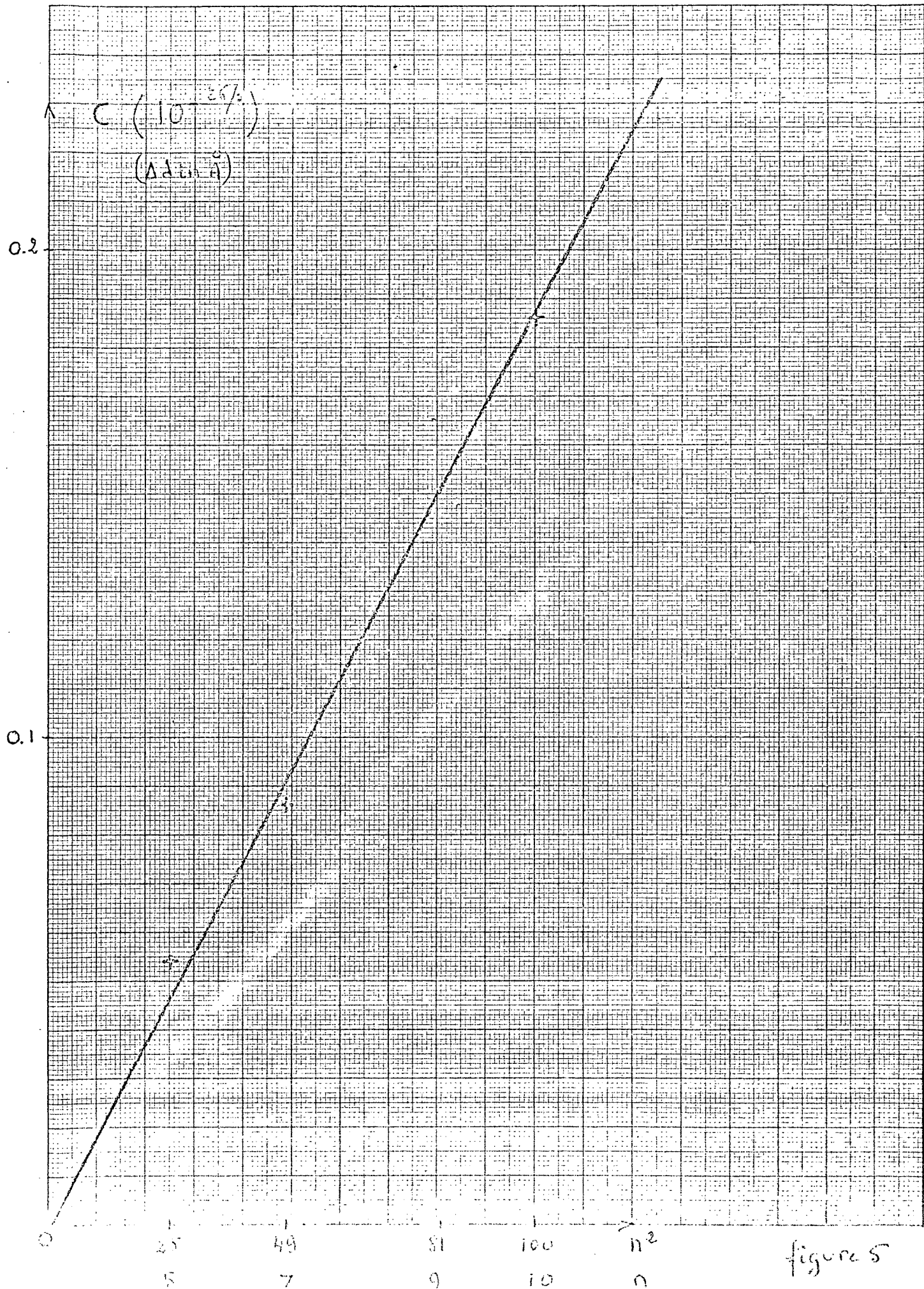


figure 5

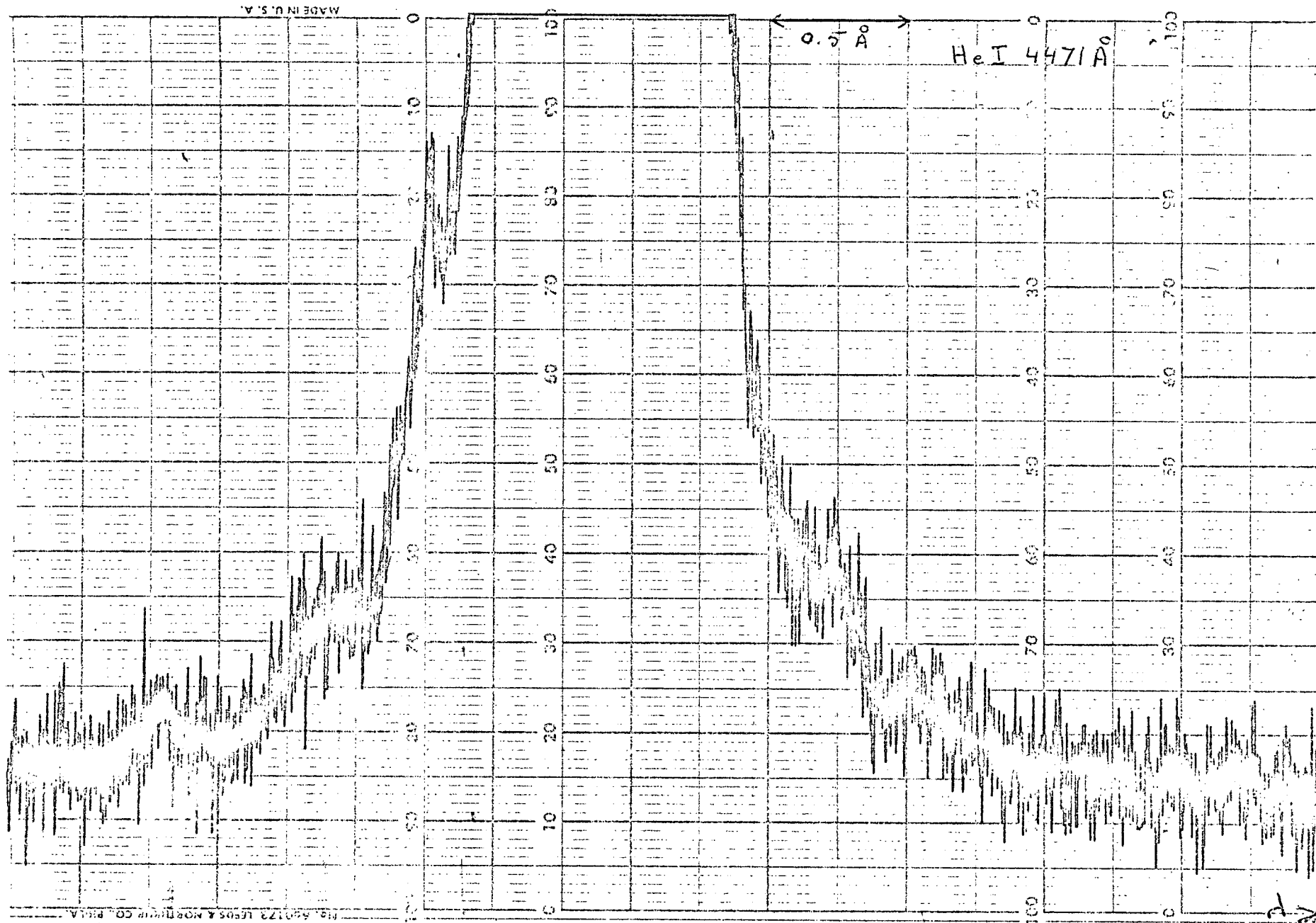


Figura 5